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Design for sustainability: The role of CAD

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ABSTRACT

The term design in this paper particularly refers to the process (verb) and less to the outcome or product. Design comprises a complex set of activities today involving both man and machine. Sustainability is a fundamental paradigm and carries significance in any process, natural or manmade, and its outcome. In simple terms, sustainability implies a state of sustainable living, viz. health and continuity, nurtured by diversity and evolution (innovations) in an ever-changing world. Design, in a similar line, has been comprehensively investigated and its current manifestations including design-aids (Computer Aided Design) have been evaluated in terms of sustainability. The paper investigates the rationale of sustainability to design as a whole – its purpose, its adoption in the natural world, its relevance to humankind and the technologies involved. Throughout its history, technology has been used to aid design. But in the current context of advanced algorithms and computational capacity, design no longer remains an exclusively animate faculty. Given this scenario, investigating sustainability in the light of advanced design aids such as CAD becomes pertinent. Considering that technology plays a part in design activities, the paper explores where technology must play a part and to what degree amongst the various activities that comprise design. The study includes an examination of the morphology of design and the development of a systems-thinking integrated forecasting model to evaluate the implications of CAD tools in design and sustainability. The results of the study along with a broad range of recommendations have been presented.

Contents

1. Sustainability 4248
   1.1. Creativity 4248
   1.2. Design, (technology) aids and sustainability 4248
   1.3. Skill and technology 4249
2. Morphology of design 4250
   2.1. Ideation 4250
   2.2. Manifestation 4252
   2.3. Synthesis 4253
   2.4. Delivery 4253
3. CAD as a design technology, and sustainability 4253
   3.1. CAD adoption – current state 4253
   3.2. CAD and sustainability 4253
   3.3. Recommendations 4254
      3.3.1. CAD – advantages 4255
      3.3.2. Innovation 4255
      3.3.3. Premature disposal of products 4255
      3.3.4. CAD usage and employment 4255
      3.3.5. Product user 4255
      3.3.6. CAD as a medium 4255
      3.3.7. Managers in the design world 4256
4. Conclusion 4256
   Acknowledgment 4256
   References 4256

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1. Sustainability

Sustainability is a fundamental principle governing life – all creatures live to survive and propagate. The progression towards sustainability also manifests in terms of species perfection and superiority and this progression is dynamic given that nature is never constant. Adaptability is fundamental in a changing environment for survival and superiority [1]. Progression and perfection of a species through mechanisms that permit extensive permutation and combination of genetic diversity are nature's way of eliminating genetic obsolescence (inbreeding) and extinction. Extinction (of species and human tribes) is a consequence of overspecialization that impedes adaptability [2]. It is this diversity that fosters the survival and health of complex ecosystems to support life indefinitely (sustainability). Modern societies and markets are akin to nature with various designs (and ideologies) competing for survival and superiority. Only the fittest survive, while the weaker perish or coalesce into new ideas (evolve). To ensure survival in a changing (competitive) environment one needs to constantly adapt and evolve by being creative [3]. Diversity in response, through creativity, is fundamental to ensure survival, superiority and sustainability.

While in the natural world, needs are predominantly of a fundamental nature (for survival and procreation), in human society demands surpass these and manifest in terms of *desired* conveniences and luxury [3,4]. The advancement of human skill and ingenuity (new ideas, tools and practices) can be attributed to pursuing needs of survival, and beyond. The intellectual capacity to continually innovate has been the single reason for the dominance of human species [5]. In modern human society the pursuit of higher needs utilising one's capabilities has been well understood as *hierarchy of needs*, solution-seeking and *design*. Design can be considered a primal innate capacity attributed to intellect and intent, viz., to survive, dominate and sustain. Capabilities and intellect devoted to understanding the design process itself are more recent [6,10].

1.1. Creativity

Creativity is a *natural* mental faculty that underlies *response* through generation of new ideas, associations or approaches. It is not confined to humans alone, even animals are creative in seeking food, safety and mates, often through the ingenious adoption of external aids/tools, viz. chimps devising flexible stems (devoid of leaves) to extract ants from anthills. Under circumstances of extreme competition, creativity is the essential edge for **survival**. Creativity is usually directed towards an intended pursuit, which may be for novelty or for a higher (economic and/or cultural) value. Just as in nature, in the product market too, competition for survival is raw and unforgiving, ensuring that only the fittest survive. Companies need to innovate (through creativity) in order to survive and thrive in an evolving (changing) market environment. Creativity is fundamentally about change (radical and progressive), one of continuity and response to changing (demands) living environments. Changes in the living environment comprise those attributed to nature, society, and economy.

Creativity is also fundamental to the enlargement of choices (*development*) and quality of life. As development occurs, human society craves for convenience and a higher living standard. To advance from the current state of existence, creative ideas and approaches are needed. Since, it is a very human urge to not maintain existential status quo, but rather keep traversing a dynamic path of development, creativity is a permanent necessity. Societies and cultures are diverse, and so are ways of interpretation, communication, problem perception, appreciation, thinking and problem-solving approaches. Diversity is a perceptible reality of life. Sustainable development is one that promotes quality of life [7], while maintaining, among other things, further attributes of humanity such as *cultural diversity* [8]. "*As a source of exchange, innovation and creativity, cultural diversity is as necessary for humankind as biodiversity is for nature*" [9]. Human development requires creativity nurtured by intellectual diversity.

According to Otto Rank, 'Creativity is an assumptions-breaking process. Creative ideas are often generated when one discards preconceived assumptions and attempts a new approach or method that might seem to others unthinkable'. It is only when people think diversely from everyone around them and before them that something new comes about. Plurality, and the lack of uniformity, is the essence of novelty and creativity. Creativity is about unconditioned free thinking, hence the need for ideation techniques such as brainstorming which precludes criticism of any sort. Creativity requires freedom from thought-constraints, conformance to standards, adherence to established paths, etc., and is about synthesizing (putting together) ideas and solutions which have originality and appropriateness. In arriving at feasible solutions it is important that the generation of seemingly inept ideas is also permitted initially.

Even among people with similar education and experience, thinking and synthesizing capabilities vary [10]. At the individual level, multi-disciplined persons are found to be more creative as permutation and combination of capabilities are enhanced. Even in collaborative creativity teams, teams with diverse compositions are known to produce ideas richer than those by teams with homogenous team-members. Diversity among team members is encouraged and orchestrated. Managers deliberately try to incorporate knowledge heterogeneity into their teams and thus provide enormous opportunities for creativity [11].

Modern society is a living bazaar ecosystem with diversity in preferences, lifestyles, choices, and product/service options. This diversity permits a wider competitive choice making the outcome richer and more beneficial [12], and as with any successful species in an ecosystem, successful products/services (ideas/designs) thrive and propagate, while the others dwindle/perish. Newer generations (people) would further alter the bazaar-ecosystem configuration.

1.2. Design, (technology) aids and sustainability

In simple terms, design is the creation (or synthesis) of something in the mind [13], subsequently externalized through a medium discernable by one or a combination of senses. This externalisation communicates the (mental) design to oneself, a working-group, an audience or client for feedback, refinement or appreciation. Externalizations represent the development of designs; they have an interactive role and a crucial effect in the mechanics of the design activity [14]. While the design initiation (and conception) and preliminary externalisations have predominantly remained a manual exercise, numerous design aids/tools are available to support subsequent design synthesis, communication, and refinement.

Current design literature provides numerous models characterising the design activity such as the Rational Model, Co-evolution model, Spiral model and Bazaar model [6,10]. The design model is best described metaphorically as a system of spaces rather than a predefined series of orderly steps, the spaces demarcating different kinds of related activities that together form the continuum of innovation [15]. Its fundamental role is to aid the designer with increasing the clarity on the design that is evolving. Design-activity sequences/processes facilitate corporate requirements of incremental innovation (as most products are not meant to be radically innovative) and rapid cost-effective product launches, but not for completely innovative products. As great designers are rare, the

incorporation of design processes will improve the performance of the entire profession. While a detailed insight into design-models is not within the scope of the paper, it is important to note that these models only serve as a general guide for budding designers and they must outgrow them rather than be bound by them. The success of a design may be estimated not only based on the remuneration to its company but also on the duration for which the design exists in usage, by either imitation or inspiration [2], and the ease and speed of its acceptance/adoption.

The creative processes being of an evolutionary nature, any tools (or design aid) used in combination with creativity must be adaptive and flexible. Conceptualization happens in the mind of the designer [16]. The design process may involve an individual imagining an idea first, bringing it into form and then communicating it to others with whom the designer may then jointly develop it further – such freedom demands that the tool/medium used be flexible. The design-aid must help the person or group communicate flexibly and generate more and richer ideas, while maintaining the diversity of those ideas. Design-aids or tools were originally physical devices such as a template or a specialty artifact that designers and artisans relied on for ensuring dexterity, advancement, extension and mastery over their specialized skill. These tools were relied on subsequent to a period of manual engagement with that skill, i.e. the tools were rarely used at the beginning, but extensively used after a certain level of skill was manually acquired. In the modern world, rapid progression of technology with advancement in computational power has reorganized the entire spectrum of extended design-aid and ability available to the designer/artisan.

Technology is the embodiment of ideas, knowledge, tools and practices which are used to meet specific needs [17]. A technological paradigm addresses a specific family of needs, uses specific principles of science and math, has a model or pattern of enquiry and is fostered by certain economic dimensions [18]. The prevalent technological proficiency has determined the nature of tools used by society to meet its needs. Design technology or aids may assist in all design activities such as conceptualization, implementation (including manufacturability), and product usage [10,19].

Design aids have been used through the ages to assist designers in their process of creating new products. The capabilities of these design aids have evolved with progress in technology. The design aid of our times has expanded to include computing power and advanced algorithms. Computer Aided Design (CAD) is one such technology used in design. CAD tools primarily aid the capture of only the structure while the description of a design involves its functionality, performance and behavior as well [20]. Design attempts to bring order to the natural chaos that develops new products [10]. A design technology must nurture the occurrence of this chaos. As an integral design tool, CAD must not interfere with the creative maneuvers at work by restricting the free thinking, which would otherwise lead to stereotypical or inflexible approaches.

Any design technology must appreciate diversity as a trait of the design processes [11]. This requires that the technology be free of single sequential paths for solutions, preconceived techniques, assumptions, distinct methodologies (because there are numerous methodologies and the technology must not vote for, or against, any methodology), constraints and standards. The interface between the human and the machine or tool must be free of distractions and hindrances to communication. A technology used in the design process must be **flexible** and (a) accommodate effective communication within a group comprising diverse designers (b) encourage generation of diverse (even inept) ideas that carry potential for new and better ideas (c) retain contradictory thoughts and unexplored ideas – even those that might appear illogical or unproven (d) integrate logic and science to aid in the synthesis of design solutions. In decreasing order, design-aids may be relied on for externalization (establishment of a design space), communication (with a design group, client group or a manufacturer) and documentation (design progress and archiving). The nature of design-aids adopted in the design profession, which originally started out to be intuitive and indigenous, has gradually become specialized and professional.

Historically, design-aids have illustrated a strong vibe with prevalent technology, viz.,

1. Sketching and colouring: the first way of conceptualizing in the history of mankind. Early humans used charcoal and plant dyes to design on cave walls. Even this very first form of design aid satisfies all the three requirements, viz. externalization (visualization), communication, and documentation.
2. Drawing aids: the invention of geometric tools: With advancements in warfare, architecture, and astronomy, new *geometric* tools were the *design aids*. The emphasis shifted away from visualization and moved towards documentation.
3. Engineering drawing: here, the goal is to accurately and unambiguously capture all the geometric features and communicate them to a manufacturer. This emerged in the time of ship building and mass production factories. The design being communicated to the manufacturers became the focus.
4. CAD: the emergence of computer as a design aid began with the aircraft industry. The advantages and adoption of CAD are discussed in Section 3.1.

Sustainability primarily deals with a healthy living environment, comprising the natural- and the built-environment, with particular emphasis on a prosperous self-reliant society amidst a stable ecosystem [3]. A self-reliant society fundamentally indicates retention of basic human capabilities and capacity to innovate, be creative and adapt (to ensure survival). Any technology aiding human creative-thinking must not substitute the same, and result in a dilution of the original human capacity. "*The best of modern technology and experience is...designed to serve the human person instead of making him the slave of machines*" [50]. With the current ubiquitous popularity and dependence on CAD among designers and manufacturers (industry) the consequent ramifications on sustainability needs to be carefully discerned. It is valid to understand and forecast how CAD will impact the design process and alter the way we meet our needs and influence sustainability of the design-community and society at large. It is crucial to arrive at a sustainability-based rationale for where CAD presently stands in the design process and where it should/should not be. The following sections deal with this rationale.

1.3. Skill and technology

Humans have used the **skills** at their disposal to meet their requirements, and, with time, enhanced these skills. A skill represents an ability acquired by training [13] and may be understood as one's ability to perform a certain task effectively. The very purpose of technology is to expand human capabilities [21] and it therefore plays a central role in the development of skills. Skills are acquired in the adoption of technology – say, in handling equipment such as a lathe or CAD. The very existence of technology implies an underlying existence of skills – skills in creation and in its usage [17]. With the incorporation of a technology, users begin to think in terms of the associated technology [22]. It is at this juncture that technology begins to influence the way users think. Designers may be induced to think in terms of the steps and processes by which desired outcomes emerge. These steps and processes are determined by the technology available. Attempts to introduce design-aids at an early design phase have led to its user describing an idea or solution in terms acceptable by the technology/machine [23,24]. To foster creativity, it is important to ideate free and neutral, not only of solutions but also of tools to achieve those solutions.

Design practice and education are driven in part by the technology available [14], and so are skills and human capabilities. Technology based skills require time for training. With changing technologies, some skills will be retained, developed and channelized while few other skills will become extinct. The loss of skills may be understood as the consequence of technology choice and progression (including obsolescence). A technology should, ideally, enhance human skills and abilities and not inhibit human capabilities, creativity or innovation. The loss of certain skills and capabilities on adopting a technology should not adversely affect the survival, stability and sustainability of future generations. While the importance of (bio)diversity and creativity is fundamental to survival and sustainability, technology often thrives under conditions of uniformity and standardization. But, uniformity inhibits diversity!

The path of a technology must accommodate diversity in development, wherein the intention is not merely to augment human abilities but also to recognize, accommodate and foster diversity in culture and the living environment. Cultural identities are crucial to sustainability as these have evolved in response to local conditions of environment, climate, resources and spiritual values (see Fig. 1).

It must also be noted that the role or influence of technology is as much as humans deliberately permit it to be. Technology can be most beneficial by being allowed to participate in some activities while kept away in others. Thus, keeping in mind sustainability as the prime driver (and current paradigm) underlying human development, the following guidelines provide an overview of the role and association between technology and design.

1. The progression and adoption of technology should not inhibit human capabilities of creative expression, innovation, decision-making or self-reliance. Technological path will determine which skills are retained and which skills are lost. (e.g. Sketching using charcoal, making dyes to paint on cave walls). The lost skills must not threaten the survival and sustainability of future generations.
2. Activities truly cerebral must still be done by the human [2]. The human conceives while the machine computes [23] resulting in an intimate co-operative complex [25]. If the machine takes over what is monotonous and repetitive, more time could then be devoted towards promotion of culture [26]. If this help is not provided, the human may, in order to economize on mental effort, resort to a habitual response, leading to similar outcomes [10] and diversity (in design) is stunted.
3. Technology should permit the designer to learn as the design process carries forward. It should be flexible and get adopted in ways desired by its diverse users. Learning of the problem, associated realities and use of aid happens during the design process [20,23].

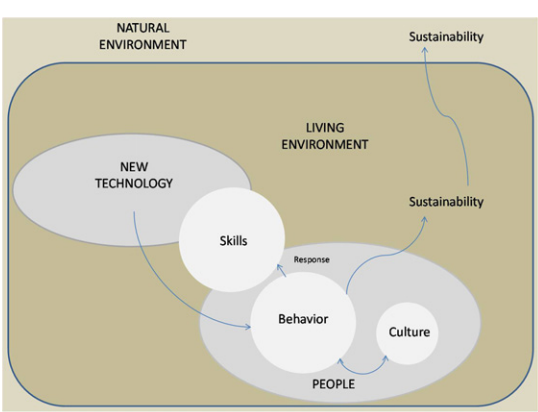

Fig. 1. Technology and sustainability.

4. Adoption of the same technology (design-aid) should not result in designers thinking alike and arriving at similar designs. Technology must encourage each designer to develop his or her own style and preserve cultural diversity.
5. Designers first think of the entire system in terms of its major sub-systems. Then, through finer refinements, more detail gets incrementally added in [10,27]. CAD tools in use today help us work backwards while a true design aid should help us design forward – arrive at a final destination as we move along the design process, with the design aid aiding us along the path. This is related to technology permitting the designer to learn aspects of the problem/design requirement as the design process progresses.
6. A technology must not become central to the design process to the extent that designers not conversant with that technology are excommunicated from the design world.

It is important to note that despite advancement in design-aid technologies, the most fundamental, or archaic, of techniques for idea/design expression/externalization such as charcoal, sand and clay have prevailed due to their simplicity and intuitive (and primal) ease. They offer unparalleled dexterity and versatility of expression only to be matched or amplified by the allied skill and mastery developed by the artist/designer (e.g. calligraphy art).

2. Morphology of design

Morphology deals with the study of the structure and form through a comprehensive articulation of its constituent parts/components. The study permits an overall appreciation of the interactions within a structure (system), its organic nature and its association with externalities. Design, fundamentally represents a mental synthesis of an idea/solution/approach with intent of artistry, novelty, convenience or problem-solving and results in an artifact (externalization). The term synthesis implies *putting together*. In the mind, this implies putting together based on one's creativity, insight, knowledge and (life's) experiences. Design can be illustrated as in Fig. 2 to understand the emergence of an idea through subsequent human–technology complex that aids design realization. This however must not be confused with the existing design (literature) methodologies that structure design as a sequence of stages to engage in to arrive at a design. The morphology of design (see Table 1) illustrates the generic structure of *design* (process) and delineates various components with their corresponding options and sub-options. The morphology is comprehensive enough to capture and represent any design in nature. Two examples, the design of a pen for college students in the modern world and the building (designing) of bird nests (as a courtship ritual) in the natural world have been represented in the morphology structure (see Table 1). The representation of the pen in the morphology has been indicated in **bold** text while that of the nest indicated as <u>underlined</u> text; **<u>bold-underlined</u>** text indicates representation of both.

This chart also describes how vital/essential/desirable the contribution of human and/or technology is to each option in the design morphology. ['vital' indicates a *fundamental* non-compromisable role; 'essential' indicates a preferred *effective* role sharing; and 'desirable' indicates a *convenient* role].

2.1. Ideation

This represents the initiation or seeding of an idea itself and is essentially a mental faculty/capacity and is usually not identified with any medium [14,28]. Sketches and other 2D and 3D representations (models) are attempts to reproduce the designer's mental images [28]. An appropriate medium is subsequently important as externalizing an idea can reduced cognitive load [29] and mentally

Table 1
Morphology of design.

Dimensions	Components	Options		Sub-options	
Initiation/ideation	Purpose	Primal		Breed	Protect/defend
		(Human$^{\text{vital}}$)		Survive/thrive	Aggression/subjugation
		Civilised		Self/social	
		(Human$^{\text{vital}}$)		**Professional/commercial**	
	State of mind/cerebral capability	Stability		Calm	
		(Human$^{\text{vital}}$)		Agitated (under stress)	
		Awareness		Narrow or broad	
		(Human$^{\text{vital}}$)		Specialised or multidisciplinary	
		Dexterity		Diversity	
		(Human$^{\text{vital}}$)		Standard/monotony	
		Scale		Individual	Cannibalization of ideas
		(Human$^{\text{essential}}$)		**Group**	Selection of ideas
	Time	Priority		Leisure	
				Immediate/urgent	
		Progression		Terminal	
		(Human$^{\text{essential}}$)		**Incremental**	
		Stability		**Peace**	
		(Human$^{\text{vital}}$)		War	
	Spatial scale	For personal space		Individual	
				Family	
		For social space		Neighborhood	
				Regional (city/country)	
	Visualization/formation	Intent		**Deliberate**	
		(Human$^{\text{vital}}$)		Spontaneous	
				Spiritual	
		Cerebral		Conscious	
		(Human$^{\text{vital}}$)		Subconscious	
		Senses		**Tactile**	
				Visual	
		(Human$^{\text{vital}}$)		Olfactory	
				Vocal	
				Aural	
				Intuition	
	Conducive factors (Human$^{\text{essential}}$); (Tech$^{\text{essential}}$)	**Environment**			
		Assistance			
		Feedback from design (e.g., visual, tactile)			
		Personal style			
Manifestation and translation	Realization process	Being synthesized *–procedure to arrive at destination*		Physical	Reworked/restart
				(Human$^{\text{vital}}$)	Incremental – [*addition/removal of sand in a sand sculpture*]
				(Tech$^{\text{essential}}$)	
				Virtual	**Reworked**/restart – [*CAD tree structure*]
				(Human$^{\text{essential}}$)	
				(Tech$^{\text{vital}}$)	Incremental –[*shape grammar*]
		Final finished form		Dimension [2D/3D]	**Physical** [painting, carving]
		(Human$^{\text{desirable}}$)			Virtual
		(Tech$^{\text{essential}}$)			
	Man–medium interaction	Stimulus by Man [*control*]		Intuitive	
		(Human$^{\text{essential}}$)		**Learned**	
		Response by medium		Receptiveness/flexibility/yieldability	
		(Tech$^{\text{vital}}$)		Dexterity	
				Intelligence	Artificial intelligence
					Contextual intelligence
	Translation medium	Realisation	2D/3D	Cerebral	Conscious
		(Human$^{\text{vital}}$)			Sub-conscious
		(Tech$^{\text{essential}}$)		Physical	Tactile, visual, smell, vocal, hearing
				Virtual	
		Share-ability	Individual		
		(Tech $^{\text{desirable}}$)	**Group**		
Synthesis – the attributes of what is finally captured	Medium	2D	Workability	Ability to repeat	
			(Tech$^{\text{essential}}$)		
				Ability to refine	
			Re-configurability	Ability to revise or make corrections	
			(Tech$^{\text{essential}}$)	Ability to confirm	
		3D	Workability	Formable	
			(Tech$^{\text{essential}}$)		
				Ability to refine	
			Re-configurability	Corrections	
			(Tech$^{\text{essential}}$)	Confirmation	
		Supported formats	Images, forms, text, etc.		
		(Tech$^{\text{desirable}}$)			
		Size of medium	Finite (e.g., sheet of paper)		
		(Tech$^{\text{desirable}}$)	Infinite (e.g., CAD, sand on a beach)		
		Collaboration	Group participation		
		(Tech$^{\text{essential}}$)	Communication	Language – Visual, verbal	
				Need for explicit communication – with/without symbols, standards	
		Retention by the medium			
		(Tech$^{\text{desirable}}$)			
		Miniaturization of designs			
		(Tech$^{\text{desirable}}$)			
	Setup	Layout of design space	Arrangement		
		(Tech$^{\text{essential}}$)	Alignment		
			Settings		
			Views		
		Tools for designing	Skill		
		(Tech$^{\text{vital}}$)	Type	Free–no tools required	
				Modified/modifiable tools permitted	
				Fixed set of tools	
	Concept generated	Shareability	Transfer of designs		**For duplication**
		(Human$^{\text{essential}}$)			For transformation
		(Tech$^{\text{essential}}$)	Feedback discussion with sharing		
		Scalability			
		(Human$^{\text{desirable}}$)			
		(Tech$^{\text{essential}}$)			

Table 1 (*Continued*)

Dimensions	Components	Options	Sub-options		
		Comparative evaluation (Human^{vital}) (Tech^{essential})	**Matching design requirements to concepts' attributes**		
			Conformance to rules	**Rules of science** **Rules of law**	
		Overall evaluation (Human^{vital}) (Tech^{essential})	Not satisfied, or troubleshooting	Foreseen result	Return to ideation
				Unforeseen result	Return to ideation
			Satisfied	Arrived at Foreseen result Arrived at Unforeseen result	
Delivery	Protocol	Language (Tech^{vital})	Buyer (Human^{desirable})		
			Manufacturer (Human^{essential})	Traditional workshop **Advanced manufacturing facility**	
		Role playing (Human^{desirable}) (Tech^{essential})	Demonstrators Audience Participants		
		Transaction (Human ^{essential})	**Money** Goodwill		
	Deliverables	Models (Human^{desirable}) (Tech^{essential})	Finished product Plan of usage **Detailed design**	Drawings Materials and processes of manufacture	
			Mock-ups Prototype		
		Alternative designs	**Product variants/family of products** (Tech^{essential}) Customization options/personalization (Tech^{vital})		
		Intellectual property (Human^{essential})			
	Destination of deliverables	Client firm	Immediate/direct usage Database		
		Manufacturing unit			

relax the designer to then concentrate on furthering the idea [28]. Designers also employ visual thinking to visualize forms and images [30–32] by devising spatial mental model [10]. It is common for designers to first postulate an idea (solution) and then react to it piece by piece [23]. The design thus evolves by successive modification and the details begin to emerge. Externalization is thus an essential requirement for iterative generation and refinement of ideas.

In this phase the designer (as human) is **vital** to understand, articulate and visualise the design, is of a certain frame of mind and is usually working under constraints of time. At this juncture,

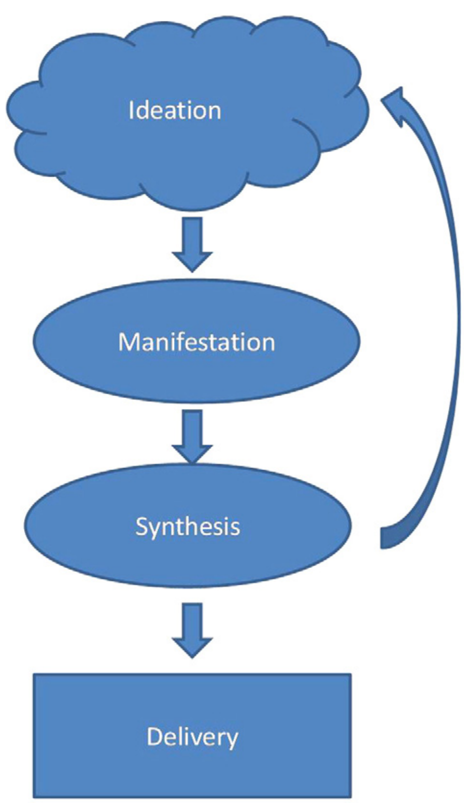

Fig. 2. Design.

technology is **essential** to provide a fertile environment for the designer to think freely in but not restrict the designer's thought process. An environment permitting free exchange of ideas is likely to generate more and richer ideas [10]. Designers tend to develop styles that manifest as a pattern of micro-decisions along the design process [10]. The style and prior experience, with expression of design thought, influence ideation and technology may aid in handling a designer's distinct style while being a common language for handling design ideas [28], and facilitating easy communication in group ideation exercises with the design-medium serving as a bridge. However, the visual cues and complex relationships a designer wishes to convey (to fellow designers), using the medium need not be discernable by the medium itself [23]. The medium must still permit this exchange to occur. Knowledge of a problem, associated realities and usage of design-aids are initially imprecise and approximate [20,23]. A design-aid should permit the design evolution from imprecise knowledge to precise design (current CAD tools are unequipped to handle imprecise information). It must encourage a wide array of possible solutions, as is in knowledge-based design systems, by assisting the designer to gather critical information about the prospective design-problem and to identify the genuine characteristics including all other aspects of lesser significance [10].

Apart from these roles, technology should generally step back during ideation as it has a tendency to be process-driven, and may hence cause more harm than good.

2.2. Manifestation

Ideation represents a spark or momentary occurrence of an idea/approach and utilizes short term memory, which is fleeting and limited in capacity. Manifestation attempts to capture that fleeting idea onto a medium. The medium's dexterity to quickly capture the idea is crucial [33,34]. To be effective, design aids must accommodate for the nature of short term memory and mental imagery in designing [14] by being fluent and flexible [29].

The designer (human) having performed the vital task of conceptualization in the ideation stage [14] needs to be succeeded by the effective and efficient capture of the idea. Technology's contribution may be considered **vital** in this design phase. The designer is primarily concerned with *what* is necessary for a medium to best elucidate his thoughts; how conducive a design-medium is

in receiving and representing this information determines the success of the technology [35]. For lucid translation, the designer must find it convenient to provide stimulus to the medium, viz., voice, motion of limbs, head, etc. [10,36]. Design-aids are still evolving to lucidly receive and translate such stimulus.

The description of a product idea may involve the expression of its structure, function and behaviour. A designer may prefer a different representation scheme for various facets of the same product and employ a combination of these schemes to best capture and communicate the thoughts [20]. The design-aid must accommodate interoperability by supporting multiple formats freely and concurrently. Research in this direction has indicated that each scheme of representation has its own advantages and disadvantages. Sketching, for example, is not the only ideal form of representation as it is passive and devoid of feasibility checks, constraint checks, simulation, analysis, etc. [37,38].

2.3. Synthesis

This represents the idea in terms of *what* is captured and includes the nature of the medium used and the attributes of the concept generated up to the evaluation of these concepts. Synthesis permits communication and collaboration in the design process and modern design technologies have evolved to network designers across the world. It is likely that design acumen and enthusiasm may shift from one member to another – with one designer leading a certain phase – the synthesis process must accommodate this [10]. Multiple formats need to be accommodated as each (designer preferred) format has its own advantages. This not only proves beneficial by effectively capturing information but also provides richness to the information captured [33,34,39], important to both manifestation and synthesis of the design. In this design stage, technology can increase its relevance by performing the **essential and desirable** roles of repetitive/iterative nature. However, the task of evaluating or judging the final concept must still **vitally** include the human.

Synthesis also represents the nature of the medium itself. For example, the benefits and appropriateness of (2D) sketching in design have been deliberated extensively in research literature [10,40]. The workability and re-configurability permitted by the medium may parallel the need to gradually evolve the design.

2.4. Delivery

This represents a time-dictated final outcome of the design for direct use or manufacture. The outcome may be in the form of detailed design drawings for manufacture and subsequent transition for use by a consumer. The delivery usually represents a protocol for the final design and allied deliverables. Communication of information for manufacturability is one of the **vital** roles of technology. Design-aids serve (externalization) communicative roles well [14] amongst fellow designers, manufacturers, clients and target test-groups. Technology can play an essential or desirable role in most other tasks in this stage. With the likelihood that customers would prefer to customize or personalize their products, the technology could play a vital role in providing an interface to receive and accommodate this customization.

3. CAD as a design technology, and sustainability

In simple terms, CAD is the incorporation of computer technology into design (process). CAD has gained ubiquitous acceptance amongst the design fraternity, including those in industry, academia and free-lancers. Designers are increasingly learning to adopt CAD at an earlier stage in the design as compared to earlier generation designers.

With advancements in affordable computing power and mature 2D/3D algorithms there are numerous reasons for choosing computers in the design process, such as

- Improved visualization, especially for increasingly complex designs.
- Interactive geometric (2D/3D) modification.
- Increase in mathematical techniques in design (including shape grammar).
- Use of CAD not requiring knowledge in computer programming [41].

3.1. CAD adoption – current state

New technologies almost always allow people to do new things as well as doing old ones better [17]. The industry today has expanded the usage of CAD technology beyond visualization, communication, and documentation to include the following.

- Correction or reversibility – steps of operations can be undone or redone.
- Standardization, reducing manufacturing costs; optimization of material configurations (cost, process intensity, weight, etc.).
- Analysis; simulation – for product working and mould flow.
- Coherence, connectivity and networking among a design team; collaboration at numerous levels of the design teams.
- Rapid prototyping and manufacturing; computer aided manufacturing (CAM).
- Reverse engineering, redefining the nature of competition in the industry.
- Tutorials and explanatory animations for product usage.
- Documentation (and archival) of designs all along the design process.

Designers may begin with schematic drawings, idea sketches, concept drawings, and then the measured drawings [33,34]. CAD is relevant only in the measured drawings phase today. The earlier stages require abstraction [28,42], which is not accommodated in CAD. During ideation, sketching is preferred to CAD because sketching permits the designer to be inexact and abstract, not compelling the designer to provide details [33–35]. Sketches support speed, fluency, flexibility and inaccuracy, all of which are necessary in the conceptual design stage. Present CAD systems are best suited for the detailed stage of design [14], although the critical stages of the design process lie much earlier [33,34]. CAD systems are still used as three-dimensional drawing boards, with added benefits. Apart from these design related adoptions, CAD technology has also propagated into other fields such as gaming and movies.

3.2. CAD and sustainability

This section specifically investigates the sustainability in Computer Aided Design (CAD) and is followed by a summary (Section 3.3) of results from the study. The study has characterized the *design world* as a system, comprising subsystems. A *systems* representation aids in discerning its various components and interactions. A system structure is an important determinant of system behavior and thus needs to be discerned and captured in depth. The increasing incorporation of CAD as a design technology in the design process must be studied from the viewpoint of the *sustainability of the design world* as a whole. The design world system has been illustrated in Fig. 3 comprising various sub-systems.

Two sub-systems in the design world are essential for creativity, viz., designers and schooling.

Designers: this represents both the traditional designers and those who use CAD as a design medium in their professional culture. This encompasses their choice of medium, design talent, skill

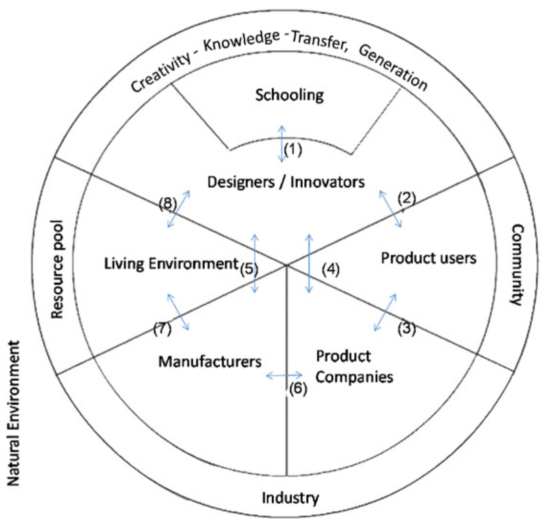

Fig. 3. The design-world system.

with medium, economic status, educational requirement and other such factors of the profession in either setting. This does not exclude self-trained intuitive designers.

Schooling: this represents the basic schooling that all individuals go through from childhood including formal design education as an adult. In basic schooling, the creative capabilities of children are nurtured to varying degrees, viz., in some they are nipped at an early stage while at the other extreme, prodigies are identified. In formal design education, the students' design skill and acumen are influenced by the adroitness of faculty members, training in engineering and sciences, exposure to various designers, design literature and design aids, interaction with artists, and investment of time in the chosen design media. A planned learning experience including diverse exposures and relevant encounters are crucial in building an *able* designer. The education of designers must recognise the limitations of formalized tutoring and hence involve critiqued practice in design education [43]. Design education should help broaden and deepen knowledge by providing exposure to both good and bad designs [10].

Product users: these are people who have needs, expectations of a product, satisfaction upon fulfillment of needs, and affections (loyalty) towards their products and surroundings. The existence of the entire system is predominantly for the users and comprises the community as a whole, including indirect users, unintended users and non-users as well. A responsible designer not only designs for the intended user but also for the community as a whole. It is the designers' responsibility to induce positive societal change through design.

Product companies: companies target market segments, hire designers and collaborate with manufacturers. They have managers who decide on issues such as target users, profit margins, and timelines. The product itself can be thought of as a child of this subsystem.

Manufacturers: these comprise both traditional artisan-workshops and highly automated factories. The production efficiency, workers' skill, health and economic well-being, living-environment consonance and product pricing are largely determined by this sub-system. The product companies and manufacturers together represent the industry.

Resource pool/environment: this represents the (natural) source of all resources and the destination of all pollutants. The entire lifecycle of the product occurs within the living environment comprising the built and the natural environment.

Critical relationships between sub-systems are indicated as numbered arrows, viz.,

1. Design practice and design education are closely interlinked as also the available technology [14]. Basic and formal design schooling play an important role in fostering the designer's creativity in professional life. Good designers nurture talent at design schools. In addition, this interaction also exposes students to learn and adapt to prevalent standard-design-practice [44].
2. Designers create products in response to the value users associate with the fulfillment of their evolving needs. Designers understand the intended/unintended impact of their products on users/non-users. Consumers also provide valuable feedback on products.
3. Product companies target customer segments, determine which technologies to provide and decide on quality and liabilities.
4. Product Companies hire designers to make products for them. The companies communicate the product brief. Managers of the product companies collaborate with designers over the product.
5. Designers prepare designs to optimize manufacturability. Designers understand the manufacturing resources available and thus minimize costs. Also the manufacturer, now no longer being the designer himself, must separately understand the design [10]. Using any technology at their disposal, the designers may best communicate the plans to the manufacturers.
6. Companies decide on whether to have in-house manufacturing or to outsource the task. This impacts the value chain [45] and the strategy of the product as a whole.
7. Factories extract raw materials and release industrial waste. Most products, at the end of their use, return to the environment. Ease of manufacturing may lead to patterns of over production and premature disposal of goods, which impact the environment.
8. Designers decide how low an ecological impact a product shall have. They decide how easily a product can be reused or recycled, thus influencing the product's relationship with the natural environment as a whole.

In addition to these critical relationships there are numerous minor interactions. Each sub-system is further broken down into *entities* comprising *variables*. Interactions within and between sub-systems are attributed to their entities and discerned through corresponding variables. The system behavior is captured through variables that interact and influence each other. This system behavior is represented using a cross-impact matrix that captures pair-wise interaction (as interaction coefficients) amongst all variables constituting the matrix [46]. The system behavior has been simulated over two decades using Kane's Simulation. KSIM is a powerful cross-impact analysis technique for forecasting real-life processes and human systems [47]. The following Section 3.3 illustrates the recommendations based on results of a comprehensive study into the impact of CAD on Sustainability based on the above system structure for the design world [48]. The direction and intensity of the trends are particularly noteworthy, and have been verified amongst a group of relevant design experts.

3.3. Recommendations

The recommendations in this paper may be broadly classified into

1. Those emerging from the guidelines mentioned on the role of technology and the design morphology.
2. Those emerging from the simulation of the design world (Section 3.2).

Table 2

Variable	Likely trend
Extent of CAD usage in the product	Steady increase until saturation
Profit to company, a concern of the managers	Sharp increase with subsequent levelling off
Product reliability	Gradual increase with eventual levelling off
Product standardization	Sharp steady increase till saturation

The recommendations from the former have been provided and substantiated as the paper progressed. These are primarily in the list of 'guidelines' (Section 1.3) on where technology should, or should not, be and represented in the morphology table (Table 1) as vital, essential and desirable tasks to be addressed by human and/or technology capability. Recommendations based on the sustainability forecast simulation-model are discussed below. The observed variable-trends in the design-world system-structure have been discussed under various facets of CAD and sustainability below.

3.3.1. CAD – advantages

As designers increasingly work to meet the needs of not only the users but also those of manufacturers and companies, the extent of CAD usage is likely to increase. An increased usage of CAD will lead to improved product reliability, standardization and profits. CAD's critical role is to connect the designers to the suppliers and manufacturers in the necessary design phase. This may result in new dynamics of data management. These trends (see Table 2) will eventually saturate as CAD nears complete incorporation into the manufacturability arena.

3.3.2. Innovation

With increased usage of CAD packages, incremental innovation will increase, while not having much of an impact on the radical innovation capability of designers (see Fig. 4).

Companies require incremental innovation more frequently than radical innovation to maintain competitive success [49]. CAD is well suited to aid efficient incremental improvements with minor design alterations. In accordance with the technology S-curve, incremental innovations will eventually saturate. Radical innovation in the product space becomes rarer as incremental innovation becomes more frequent. Products will not be radically innovative until incremental innovation cycles have been completed over previous radical innovations.

It is important for the design community to understand that in its present form, CAD is less conducive to radical innovation by concentrating on the communication and documentation, losing out on what drew designers to design-aids in the first place – *design space for externalization*. It is the ability to effectively capture a fleeting idea on to the medium and to think differently that is likely to improve design quality. CAD packages must aspire to assist the designer in these aspects, for if they do not, then they will continue to be a tool satisfying only the secondary objectives while ignoring the primary. This inadequacy is evident in the recent trend of emergence of CAD packages with the sole objective of helping designers innovate.

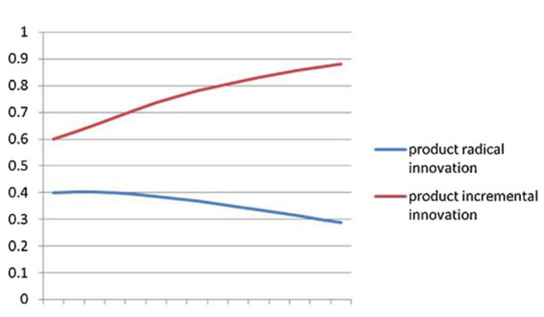

Fig. 4. Trend in product innovation.

Table 3

Variable	Trend description
Extent of CAD usage in the product	Steady increase until saturation
Pollution due to premature disposal of goods	Large steady increase with delayed levelling off
Pollution due to industrial and computer waste	Large steady increase until levelling off

3.3.3. Premature disposal of products

The adoption of CAD will likely hasten the process of innovation. As innovations (both radical and incremental) become increasingly frequent, new products emerge more frequently, leading to products becoming outdated (or obsolete) sooner. Although these products are usually designed for a longer life, users may choose to dispose of these products in exchange for newer versions. Products may not live out their intended life spans, resulting in unnecessary waste-generation, excessive consumption of raw materials, and pollution (see Table 3). Designers will soon have to design products to accommodate up gradation, reuse of sub-components, and premature retirement. This system behavior would also see the emergence of a strong used-product sales market.

3.3.4. CAD usage and employment

An increasing incorporation of CAD encourages automation of manufacturing facilities. Automation will require fewer but better skilled workers at factories. The worker strength in existing computer-aided factories is likely to decline. The number of employees in traditional workshops is likely to decrease as standardization and automation would edge-out local products. The resulting unemployment in traditional factories is likely to increase steeply in the near foreseeable future (see Table 4). The traditional equation of factories serving as avenues of local-employment is likely to change across the developed and developing worlds.

3.3.5. Product user

As product replacement increases, it is likely that users increasingly feel less attached or passionate about their products. Buyers' fatigue gradually sets in, making people care progressively less about their products, and consume (and generate waste) more. Designers must endeavour to discourage this trend (see Fig. 5). Products must be designed to value the affections (loyalty) of their users in order to foster long product life and also reduce waste generated (to be sustainable).

3.3.6. CAD as a medium

A mild increase in the intuitive receptiveness of the medium is likely, and this would greatly improve the usage-experience of the medium. The ease of CAD usage is expected to reach a saturation point at which there will be seamless manifestation (or realisation) of designer ideas. The success of a design technology must, as already discussed, reflect its ability to capture the thoughts of the designer.

Table 4

Variable	Trend description
Extent of CAD usage in the product	Steady increase until saturation
Staff strength at traditional workshops	Gradual steady decrease
Staff strength at computer-aided workshops	Large steady decrease until levelling off

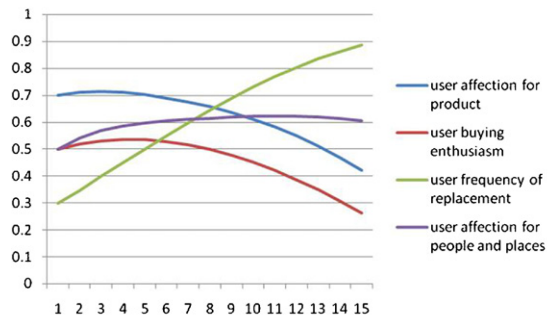

Fig. 5. Product-user trends.

3.3.7. Managers in the design world

As CAD is envisaged to help communicate the idea of the product to managers more lucidly, the need for engineer–managers is likely to decline. CAD can help designers effectively communicate with companies, manufacturing staff and potential users. Product strategy at companies is likely to be less of engineering and more of strategizing (with increased non-engineer managerial role) as CAD makes products more communicable. It is important to note that the innovative value of the design is unlikely to be affected by whether the decision-makers at these companies understand it or not. However, the pace of radical innovation is likely to slow down.

4. Conclusion

This paper primarily addresses design as a process and investigates the role of design-aids on sustainability. Sustainability in design implies the retention of human innovation and creativity for diversity. Diversity is fundamental to adaptability and survival, and in the design (market) world it provides the competitive edge and determines survival and success. A morphology of *design* has also been devised to represent the organic nature of design and also identify the role of human and technological capability/capacity in design. Finally, results of a study involving a simulation model to evaluate and forecast the role of CAD in design and sustainability have been discussed. Recommendations for sustainability in design have also been articulated in this paper.

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